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# THE USE OF REMOTE SENSING IN A GEOLOGY, ENERGY, AND MINERAL (GEM) RESOURCE POTENTIAL EVALUATION

Prepared for

U.S. BUREAU OF LAND MANAGEMENT

DIVISION OF SCIENTIFIC SYSTEMS DEVELOPMENT

DENVER SERVICE CENTER

Submitted by

ERTEC WESTERN INC. (Formerly Fugro Inc.)

3777 Long Beach Boulevard

Long Beach, California 90807

November 20, 1981

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ACT NO. YA-512-CTB-232 PROJECT NUMBER 78-281

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# I. INTRODUCTION

# I. INTRODUCTION

This report presents the results of a test case study to evaluate the use of remote sensing data in the solution of Bureau of Land Management (BLM) Geology, Energy, and Mineral (GEM) resource problems. The project was performed under BLM Contract No. YA-512-CTB-232 and coordinated through the Division of Scientific Systems Development of the BLM-Denver Service Center.

## Objectives

The primary objective of the study was to evaluate the applicability of using remote sensing data, particularly Landsat multispectral data and stereo aerial photographs to outline the GEM resource potential in a test area of northwestern Arizona. The ultimate goal was to test the results of the recommended methodology for making resource and land use planning decisions.

To accomplish the objectives a three-phased study was undertaken. Phase I consisted of a detailed literature search and mapping four parameters directly from computer enhanced Landsat imagery and small-scale stereo aerial photographs: 1) drainage patterns, 2) landforms, 3) cover types, and 4) linear features.

Phase II required mapping structural geology/geodynamics, lineaments, stratigraphy, and geomorphology. Phase II was based on Phase I data, small- and large-scale stereo aerial photographs, and data from the literature.

Phase III combined data from Phases I and II to produce the final evaluation of resource potential of the test area. A limited field reconnaissance was undertaken to check some of the more critical and/or problematical interpretation areas.

The following sections of this report will discuss the overall test methodology, the location of the regional study area and the small areas selected as intensive study areas $I_1$ and $I_2$, the geologic setting, the analysis and interpretation of the Landsat data, the geologic interpretations, and the interpreted resource potential. Following the data presentation and discussion, the report presents a comparison of the results obtained from the various remote sensing data, a discussion of the suitability of the employed methodology, and conclusions and recommendations.

## Methodology

The first phase of the three-phased study was composed of two basic tasks: literature compilation and mapping four geologic characteristics from computer enhanced Landsat imagery and

small-scale stereo aerial photographs. A detailed literature search was conducted to find all available, published material pertinent to the GEM resource potential of the study area. The search included state and federal government agencies, public offices, university theses files, and private sources. A detailed reference list is presented in Chapter IX References. Simultaneously, a review of available Landsat computer compatible tapes (CCT's) for the entire study area was performed, and a tape that met certain quality, cloud cover, and time of the year standards was selected. The CCT's were then purchased and digitally enhanced and the resultant image was enlarged to about 1:250,000 and used as the mapping base for the entire study area. A description of the enhancement procedure is presented in Chapter III, Presentation of Landsat Data.

Four geologic/geomorphic characteristics were mapped on acetate overlays from the enhanced Landsat image for the entire study area: drainage patterns, landforms, cover types, and linear features. These data were supplemented with more detailed information from interpretation of small-scale (1:120,000) color infrared (CIR) stereo aerial photograph positives viewed stereoscopically on a light table. Descriptions of the geologic characteristic overlays are presented in Chapter III, Presentation of Landsat Data.

The Phase II studies focused on producing geologic interpretations of geologic structure/geodynamics, lineaments, stratigraphy, and geomorphology. The characteristics were mapped at an approximate scale of 1:250,000 directly on the Landsat image. These data are presented as colored overlays on Plate 1 and reduced versions are presented as Figures in Chapter IV, Geologic Interpretations. The interpretations were supplemented with Phase I data. The two intensive study areas were studied in greater detail using large-scale (1:60,000 and 1:30,000) stereo aerial photographs. These data were then composited onto 1:50,000 scale topographic basemaps for the two intensive study areas and are presented as Plates at the end of this report. Chapter IV, Geologic Interpretations, presents a detailed discussion of the Phase II interpretations.

Phase III had two primary tasks; interpretation of GEM resource potential and minimum field reconnaissance (about 5 days). Originally field reconnaissance was planned to take place between Phases II and III. However, after completing Phase II it was decided that delaying the field effort until after the completion of Phase III was advisable. Phase III utilized information gathered and generated in Phases I and II and interpreted or extrapolated these data to derive the GEM resource potential. The data were then summarized into four resource potential categories: 1) leasable energy

resources (oil, gas, coal, and geothermal), 2) salable industrial resources (sand, gravel, etc.), 3) locatable mineral resources (uranium, etc.), and 4) water resources (ground and surface). These interpretations are only presented for each of the two intensive study areas ($I_1$ and $I_2$) (Figures 11 and 12).

A brief field reconnaissance was performed to check some of the more critical areas in the detailed (intensive) study areas. The emphasis of the field checking was on examining areas of known mineral occurrences to determine their most likely origin; whether they were small, localized deposits or had origins suggestive of a more widespread distribution.

# II. LOCATION

# II. LOCATION

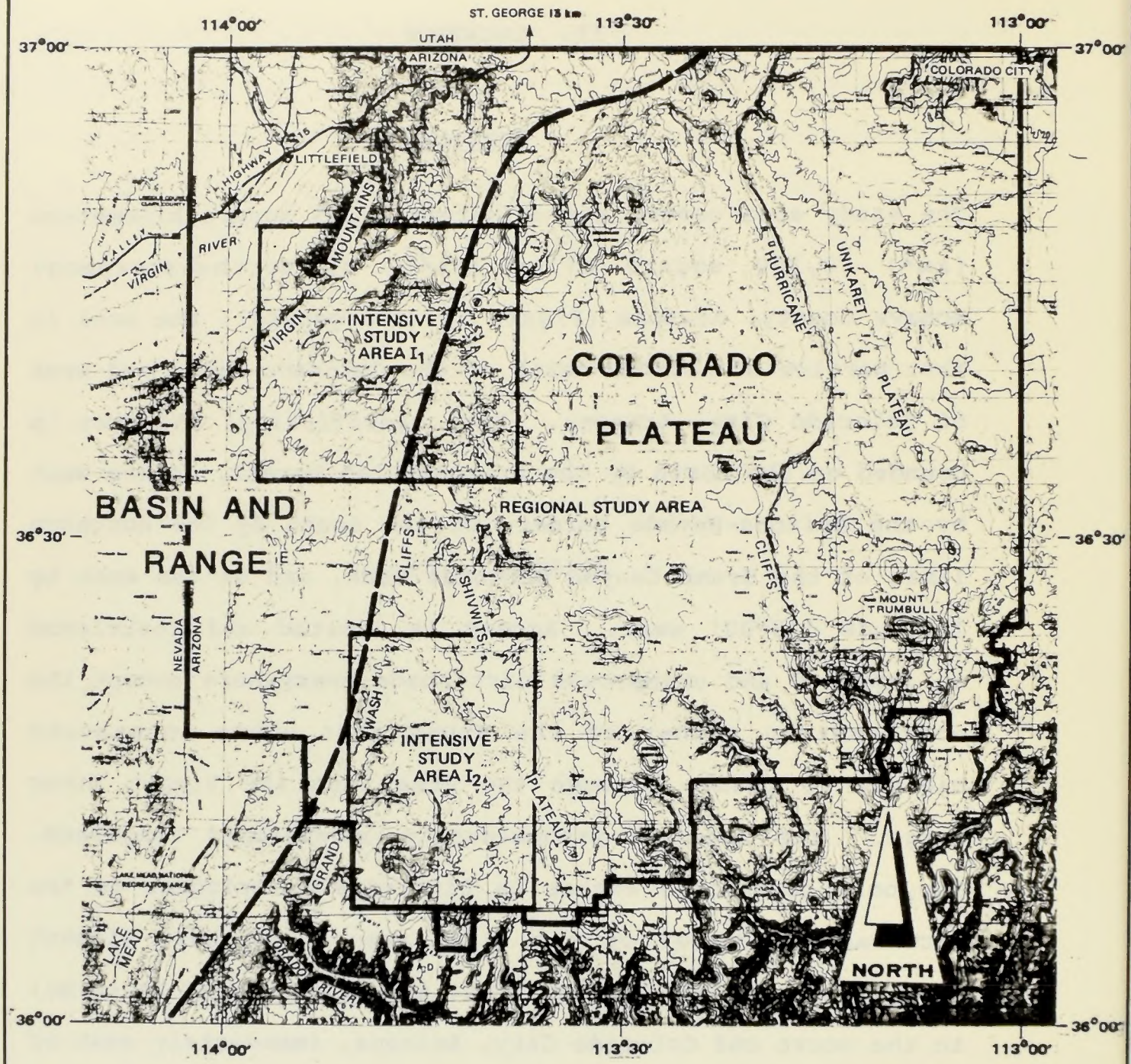
## Regional

The study area covers approximately 8,325 square kilometers ($km^2$) (3,300 square miles [$mi^2$]) of northwesternmost Mohave County, Arizona (Figure 1). In general, the area is that portion of Arizona north of the Colorado River and west of Colorado City, Arizona. More specifically, the area is bounded on the north by the Arizona-Utah border, on the west by the Arizona-Nevada border, on the south by the northern limit of the Grand Canyon National Park, and on the east by latitude 113°00' west. Access is limited and restricted to improved and unimproved dirt roads everywhere except the northwestern corner of the study area where interstate highway 15 passes through the area into the Virgin River Gorge. The area is predominantly undeveloped rangeland. The only population center is Littlefield, Arizona, in the northwestern corner of the study area. The next closest settlements are St. George, Utah, approximately 13 km (8 mi) to the north and Colorado City, Arizona, immediately east of the northeastern corner of the study area.

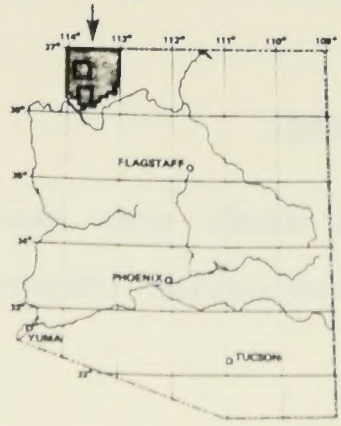
## Intensive Study Areas

Two smaller areas within the regional study area were designated by BLM for more detailed investigation (Figure 1).

# STUDY AREA LOCATION MAP




STUDY AREA




EXPLANATION

STUDY AREA BOUNDARY

INTENSIVE STUDY AREA BOUNDARIES

PHYSIOGRAPHIC PROVINCE BOUNDARY

0 10 20 MILES

0 10 20 KILOMETERS

FIGURE 1

They are identified as intensive study areas $I_1$ and $I_2$. $I_1$, the northernmost of the two intensive study areas, is located near the northwestern corner of the regional study area. $I_1$ is nearly a square with about 18 km (11 mi) on a side, 840 sq. $km^2$ (324 $mi^2$). The center of the area is about 37 km (23 mi) south to southwest of St. George, Utah, and 24 km (15 mi) southeast of Littlefield, Arizona. There are no population centers within intensive study area $I_1$. Access is by dirt road from the north out of St. George and on the west from Mesquite, Nevada. The area includes the Virgin Mountains of Arizona, Black Top Mountain, and the plateau country immediately to the east.

Intensive study area $I_2$ is located approximately 18 km (11 mi) south of the southern boundary of $I_1$. $I_2$ is rectangularly shaped with its long axis oriented north-south. The area comprises about 675 $km^2$ (260 $mi^2$) with the Grand Wash Cliffs nearly marking the western boundary. Pigeon Canyon passes east-west through $I_2$ a little north of center. The center of the area is about 84 km (52 mi) south-southwest of St. George, Utah, and approximately 8 km (5 mi) north of the Colorado River at its closest approach. Access is almost entirely from the north and east on dirt roads although less traveled routes from the west do exist. The area is located primarily on the Shivwits Plateau.

## Geologic Setting

The regional study area is located in the transition zone between two physiographic provinces (Figure 1): the Basin and Range on the west and the Colorado Plateau on the east. The Colorado Plateau occupies the eastern three quarters of the study area and the Basin and Range the western quarter. The two provinces are generally divided along the Grand Wash Cliffs in the southern part of the area. This boundary moves eastward near the Utah-Arizona border where it is generally marked by the Hurricane Cliffs in Utah.

Fault block mountains and internal drainage are the typical characteristics associated with the Basin and Range Physiographic Province. However, in the study area the Basin and Range portion consists of the bajada landscape in the Virgin River Valley on the west side of the Virgin Mountains, the Virgin Mountains, and the extensive alluvial plains to the south. Drainage is external to the Virgin River which flows southward to the Colorado River drainage. The Virgin Mountains are a complexly folded and faulted mountain range bordering the Colorado Plateau and reaching elevations in excess of 2,225 m (8,000 ft). South of the Virgin Mountains is a lava covered plain forming tablelands dissected by numerous, dry stream channels. These streams, joined by southwest and west trending streams originating at

the Grand Wash Cliffs flow westward to the Virgin River and Lake Mead.

The Colorado Plateau portion of the study area is typified by nearly flat-lying strata which dip very gently to the northeast. Except along the deep incised canyons of the Colorado River, drainage is northerly to the Virgin River, south of St. George Utah. Elevations on this part of the Colorado Plateau are basically over 1,400 m (5,000 ft) and reach maximums over 2,225 m (8,000 ft) at Mount Trumbull.

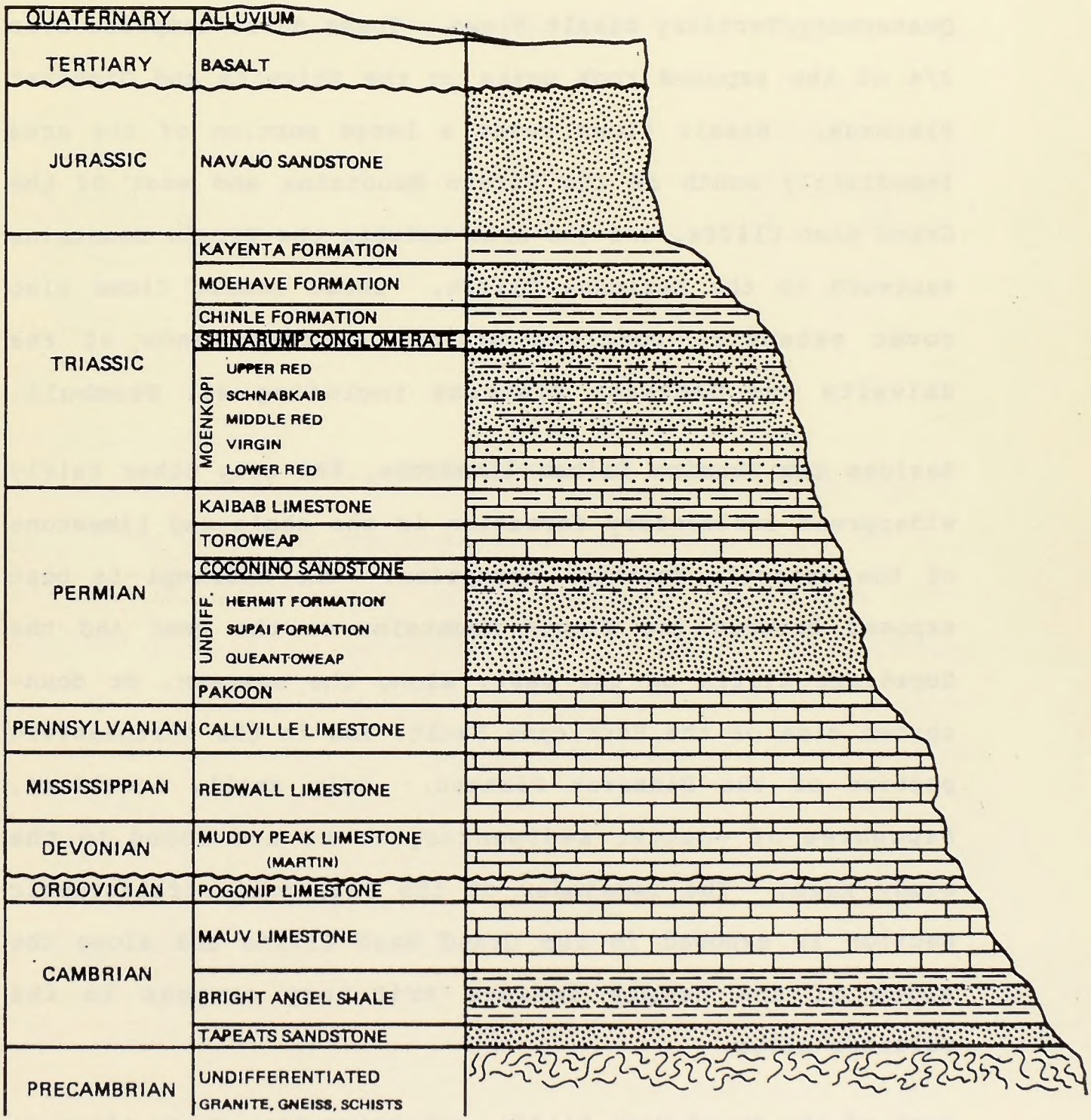
In general, the area is subdivided by broad, nearly flat plateaus oriented in steplike fashion east-west across the study area. Numerous volcanic cones and basalt flows cover the surface. The separate plateaus were formed by and are presently bounded by major north-south trending escarpments or fault-line scarps representing normal faults, downthrown on the west side. The western border of the Colorado Plateau is marked by the escarpment of the Grand Wash Fault which displays up to 1,110 m (4,000 ft) of offset near the Colorado River (Hamblin and Best, 1970). This highly dissected escarpment also marks the western edge of the Shivwits Plateau, the westernmost subdivision of the Colorado Plateau. The surface of the Shivwits Plateau slopes gently eastward for approximately 48 km (30 mi) to the base of the Hurricane Fault which displays up to 1,670 m

(6,000 ft) of offset (Hamblin and Best, 1970) and which denotes the edge of the next subdivision, the Uinkaret Plateau. The Uinkaret Plateau is similar to the Shivwits Plateau and is characterized by mesas and tablelands with lava caps. Many Cenozoic volcanic cones and lava flows dot the Uinkaret and Shivwits plateaus. The eastern border of the Uinkaret Plateau is marked by the Toroweap-Sevier Fault which only enters the study area at the southeastern corner. Many minor normal faults also cut the plateau area. Most are typically downthrown on the west side with a few downthrown on the east side forming small, graben-like structures. Only minor folding has occurred throughout the study area.

The stratigraphic sequence in the study area consists of thousands of meters of Paleozoic, Mesozoic, and Cenozoic sediments deposited on the Precambrian crystalline basement complex and, in areas, overlain by younger basalt flows and alluvium (Figure 2). Precambrian granite, granite gneiss, and related crystalline intrusive rocks are exposed in the Virgin Mountains and at the bottom of the Grand Canyon. Overlying these basement rocks, thousands of meters of sedimentary units are exposed in the typical Grand Canyon section, ranging from the Cambrian Tepeats sandstone to the recent sediments in modern stream channels.

Most important to the study are the exposed rock units. Already mentioned are the Precambrian rocks in and around

# STUDY AREA
# GENERALIZED STRATIGRAPHIC COLUMN




NOTES:

1. MODIFIED FROM BLM SOLICITATION NO. YA-512-RFP8-96
2. NO VERTICAL SCALE

FIGURE 2

the Virgin Mountains. The most extensive rocks exposed in the study area are the Permian Kaibab Limestone and the Quaternary/Tertiary basalt flows. These units comprise over 3/4 of the exposed rock units on the Shivwits and Uinkaret Plateaus. Basalt flows cover a large portion of the area immediately south of the Virgin Mountains and west of the Grand Wash Cliffs, and the area between the Virgin Mountains eastward to the Huricane Cliffs. These basalt flows also cover extensive portions of the southern ends of the Shivwits and Uinkaret Plateaus including Mt. Trumbull.

Besides the Permian Kaibab limestone, the only other fairly widespread sedimentary formation is the shale and limestone of the Triassic Moenkopi Formation. The Moenkopi is best exposed between the Virgin Mountains on the west and the Hurricane Cliffs on the east, along the western, or down-thrown side of the Hurricane Fault, and in the northeastern portion of the Uinkaret Plateau. Only small, localized, exposures of younger sedimentary rocks are found in the study area. The remainder of the Paleozoic stratigraphic section is exposed in the Grand Wash Cliffs and along the sides of the deeply incised tributary canyons to the Colorado River.

West of the Grand Wash Cliffs, extensive Quaternary alluvial plains comprise a large portion of the western quarter of the study area. Included in this group is the extensive bajada along the western side of the Virgin Mountains.

# III. PRESENTATION OF LANDSAT DATA

# III. PRESENTATION OF LANDSAT DATA

## Analytical Techniques

### Scene Selection

The following factors were considered for selection of the Landsat scenes used in this study: 1) availability of consecutive scenes, 2) time of the year, 3) percent snow cover, and 4) EROS Data Center (EDC) quality and cloud cover ratings. Consecutive scenes were important because two scenes, path 41 rows 34 and 35 had to be combined or mosaiced to cover the entire study area. The mosaic process can be performed on any adjacent scenes but is easiest and most economical on consecutive scenes. Because of the repetitive nature of the Landsat data (18 days repeat cycle), consecutive here means two scenes taken consecutively on the same satellite orbit.

The time of year the scenes were taken is important because of the effect the angle of the sun has for geologic interpretations. A moderate to low sun angle will enhance some geologic/topographic aspects of the terrain. Based on this fact, late fall to early spring scenes without any snow cover were considered optimal.

The EDC has quality and cloud cover statistics on all computer data in their Landsat files. These data range from

0-9 for quality with 9 being the best, and 0% to 100% for cloud cover. Only scenes with quality ratings of 8 or better and 0% cloud cover were considered for use in this study.

Based on these criteria, two consecutive Landsat scenes taken on October 10, 1977 (scene nos. 8298317051500 and 8298317054500) were selected. Computer compatible tapes (CTT's) were then purchased and computer processed specifically for this study.

Computer Processing

Computer processing of the CCT's was performed by Battelle Pacific Northwest Laboratories. The following is a brief description of their hardware system: The heart of the hardware system is a network of four DEC PDP 11 processors (two 11/55's and two 11/70's) connected to a total of nearly 1.6 billion bytes (unformatted capacity) of on-line disk storage. The hardcopy graphic output of the four CPU's is handled by a PDP 11/34 processor. Six 9-track tape drives of varying performance levels are available for entering and saving image data.

A complete set of graphical input and output devices are interfaced to the systems, including a digitizer table, an A/D converter, a card reader, an interactive vector scope, several graphics preview scopes (memory type), a color CRT

display, a CalComp plotter, a film recorder, and an electrostatic printer/plotter.

The CCT's for the two Landsat scenes were digitally combined and contained the southern third of scene number 8298317051500 and the northern two-thirds of scene number 8298317054500. The combined image was then preprocessed prior to image enhancement. A select group of computer enhancements geared specifically to the geological nature of the work were selected to maximize data, yet maintain scope and budgetary constraints. These enhancements were finalized on an interactive display system for best results.

Preprocessing or image restoration refers to processes that "recognize and compensate for data errors, noise, and geometric distortion introduced in the scanning and transmission process" (Sabins, 1978). What this accomplishes is to "make the image resemble the original scene" (Sabins, 1978). Preprocessing on the project image included a geometric correction, a noise correction, and a dropline correction.

Image enhancement refers to the "modification of an image to alter its impact on the viewer" (Sabins, 1978). For this project an edge enhancement and a nonlinear contrast stretch were performed. The edge enhancement was to accentuate sharpness of linear features for mapping structural geology

and lineaments. The contrast stretch was to maximize the overall contrast of the particular scene to help distinguish landforms, cover types, stratigraphy and geomorphology. These enhancements were selected to provide the maximum data for the geological interpretations for this study and to remain in budgetary and contractural restraints. The restored composite image was resampled using a nearest neighbor interpolation routine to produce an image with 3120 by 3120 square pixels. An 11 by 11 element uniformly weighted box filter was applied to the image for edge enhancement. Each of the four bands was contrast-stretched using a nonlinear stretch function generated by an interactive enhancement program. These contrast functions were subsequently applied to the image to produce hard-copy output on the DICOMED digital image recorder. The final color composite at 1:250,000 was produced by using the following color assignments:

| Color | Band |
|---|---|
| Red | 7 |
| Green | 5 |
| Blue | 4 |

## Interpretation

### Descriptive Units

The image interpretation overlays were produced from the Landsat image and small-scale stereo aerial photographs.

Data on drainage patterns, landforms, cover types, and Plates 1 through 8. The descriptive units used to delineate these characteristics have been devised from several sources (U.S. Geological Survey, 1978; Anderson and others, 1976; O'Leary and others, 1976). The units used herein are combinations fashioned to the scope and objectives of this study. A detailed explanation of these units is presented in Table 1; abbreviated descriptions are presented on the individual Figures and Plates.

Drainage Patterns (Figure 3 and Plates 2 and 3)

Stream channels are primarily identified as areas of shadow, indicative of a topographic low on the Landsat image. Many stream channels are also reflected by light-toned areas where erosion has taken place through the dark basalt flows.

Drainage in the study area is predominantly dendritic in the plateau areas with some portions reflecting structural control through jointing and/or fracturing producing a near-rectangular pattern. The steep canyon tributaries are characterized by parallel drainage. The alluvial plains and bajada areas exhibit anastomosing stream channels indicative of the relatively flat, sloping surface such as an alluvial fan.

TABLE 1

DESCRIPTIVE UNITS FOR GEOLOGICAL CHARACTERISTICS (PHASE I)

| Symbol | Description |
|---|---|
| | **Drainage Patterns** |
| | All stream channels mapped in the study area. Represents ephemeral and/or intermittent streams. |
| | **Landforms** |
| F | FLUVIAL: landforms directly attributable to stream-laid deposits. |
| FF | ALLUVIAL FAN: fluvial landforms characterized by gently sloping topography, a general fan-like form in plan view apexing where drainage lines emerge from mountainous terrain, and anastomosing drainage lines. |
| FB | BAJADA: fluvial landforms characterized by sloping topography developed as a continuous apron flanking major mountain ranges (coalesced fans). |
| FV | FILLED VALLEY/VALLEY FILL: fluvial landforms characterized by flat, irregular shape, braided drainage pattern, typically located in intramountain valleys. |
| FT | TERRACE: fluvial landforms characterized by very gentle slopes with a steeper ascending slope on one side and a steeper descending slope on the opposite side. Restricted to the area along the Virgin River in the study area. |
| VF | VOLCANIC FORM: landforms directly attributable to volcanic eruptions. Includes volcanic cones; landforms with conical or subcircular shape with steep slopes, and radial drainage, and volcanic flows; landforms with steep, cliff-like outer edges that form plateau- or mesa-like features typically associated with volcanic cones, and filling or covering pre-existing topography. |
| P | PLATEAU: landforms characterized by relatively flat topography developed over a regional extent. |

TABLE 1 (Continued)

DESCRIPTIVE UNITS FOR GEOLOGICAL CHARACTERISTICS (PHASE I)

| Symbol | Description |
|---|---|
| E | ESCARPMENT: cliff-like landforms characterized by steep topography with gentler slopes both above and below. |
| M | MOUNTAIN: terrain characterized by steep, irregular topography, numerous first order drainages, and sparce vegetation. |
| HB | HOGBACK (FLATIRON): landforms characterized by a long, narrow ridge or series of hills, structurally controlled by the presence of homoclinal sedimentary strata that dip steeply. |
| | Cover Types |
| Rc | Bedrock exposures (consolidated) |
| Ru | Unconsolidated units (alluvium, etc.) |
| Vn | Natural vegetation |
| Vr | Rangeland (developed) |
| A | Agricultural Fields |
| | Linear Features |
| | All linear features are mapped according to the definition of linear given by O'Leary (1976): "Linear. L. linea = line + L. aris = of, or belonging to; hence, of or relating to a line; denoting the properties of a line. Linear is an adjective that describes the line-like character of some object or objects." There are no geological connotations applied to the definition of linear feature. |

# DRAINAGE PATTERNS

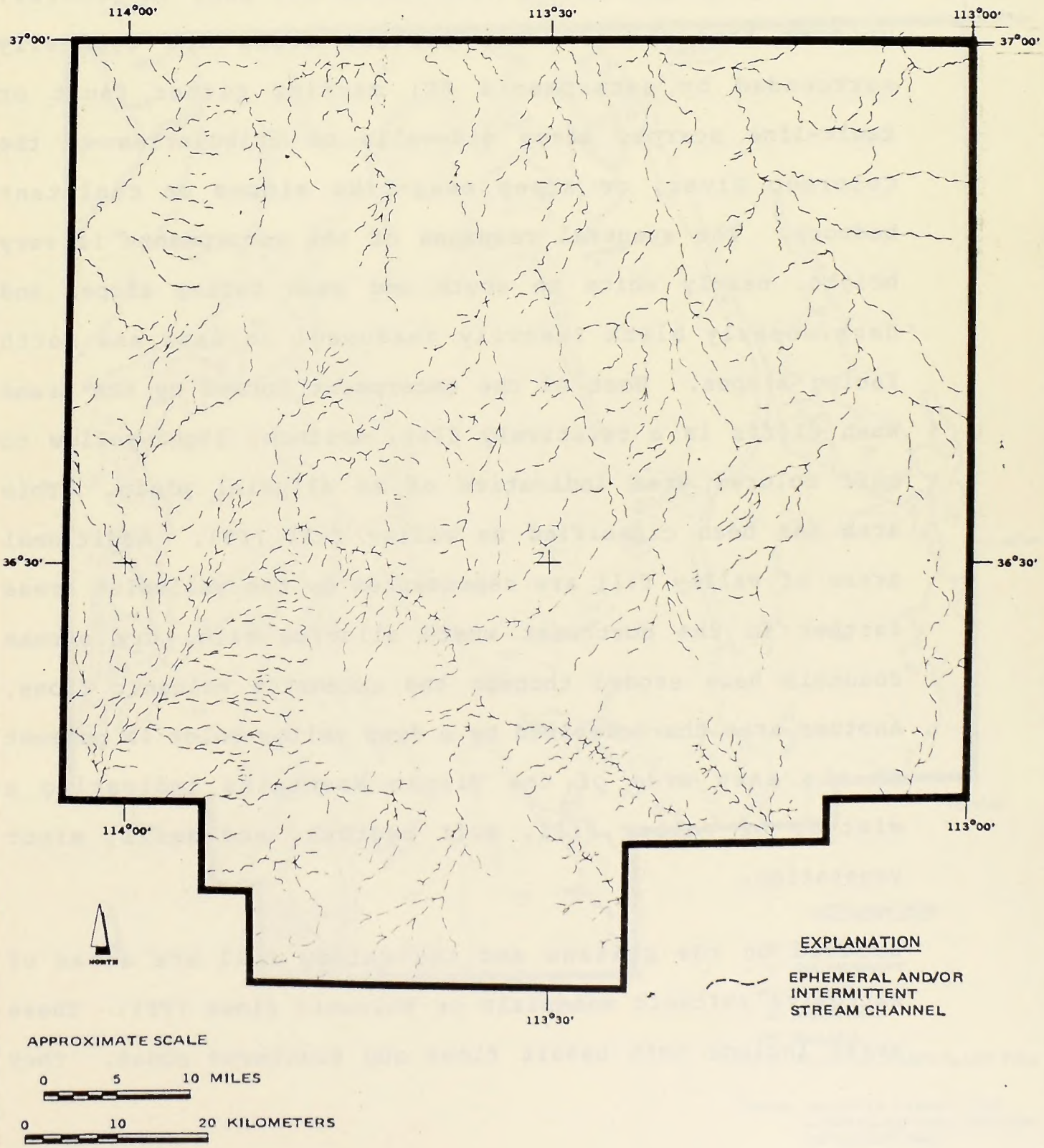


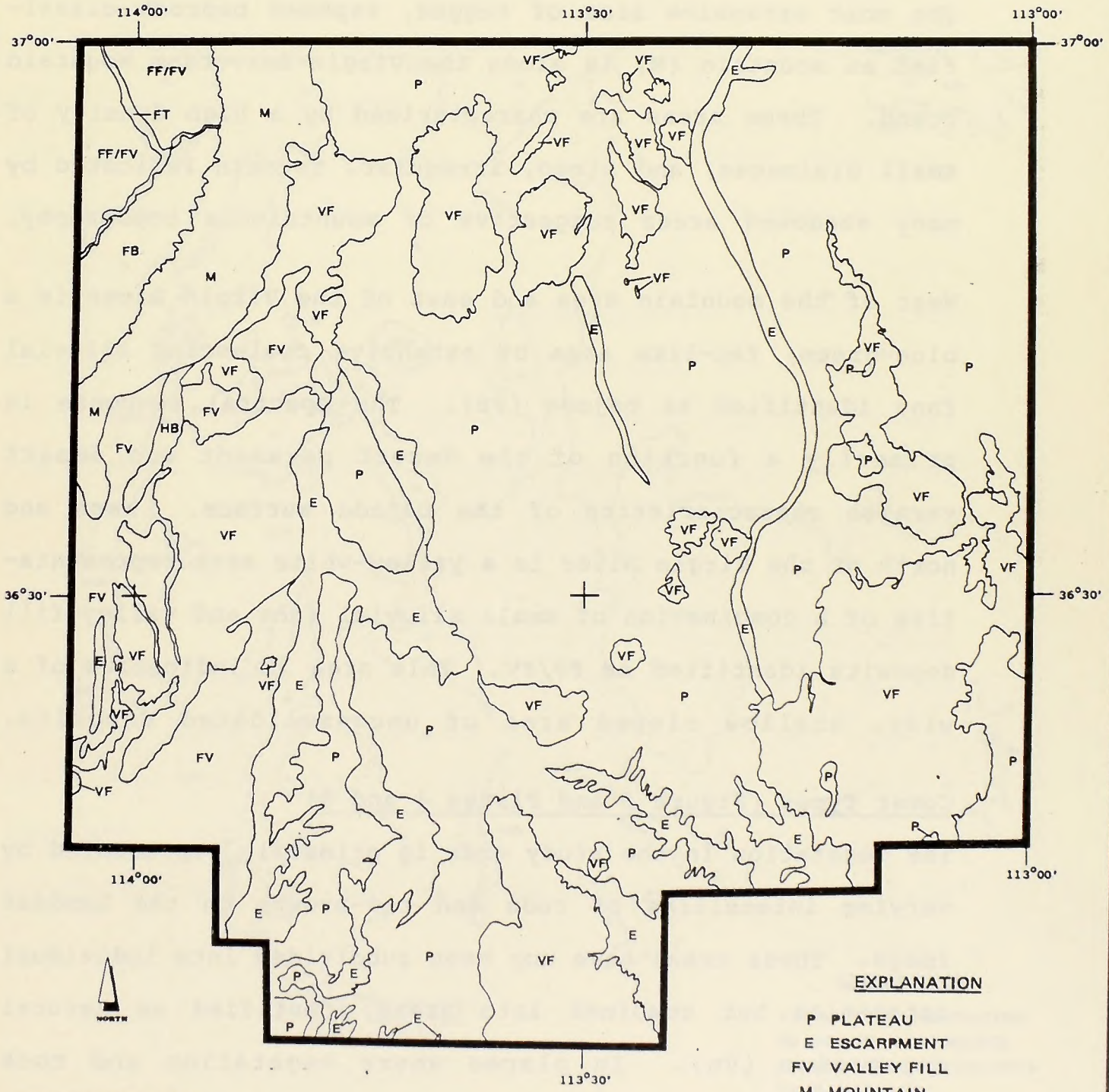

FIGURE 3

Landforms (Figure 4 and Plates 2 and 3)

The predominant landform in the study area is the vast plateau regions (P) of the Colorado Plateau. These areas have varying degrees of dissection but are, in general, uniform throughout. The plateau areas are typically surrounded by escarpments (E) marking either fault or fault-line scarps, steep sidewalls of tributaries to the Colorado River, or steep mesa-like slopes on resistant bedrock. The spectral response of the escarpments is very bright, nearly white on south and east facing slopes and dark, nearly black (heavily shadowed) on west and north facing slopes. West of the escarpment formed by the Grand Wash Cliffs is a relatively flat, uniform, light-yellow to buff colored area indicative of an alluvial plain. This area has been classified as valley fill (FV). Additional areas of valley fill are represented by the yellowish areas farther to the northwest where alluvium rich, dry stream channels have eroded through the extensive volcanic flows. Another area characterized by a deep yellow color is present on the east side of the Virgin Mountains indicating a mixture of valley fill, soft bedrock, and small, minor vegetation.

Located on the plateau and the valley fill are areas of extrusive volcanic materials or volcanic flows (VF). These areas include both basalt flows and scattered cones. They

# LANDFORMS




APPROXIMATE SCALE

0 5 10 MILES

0 10 20 KILOMETERS

EXPLANATION

P PLATEAU
E ESCARPMENT
FV VALLEY FILL
M MOUNTAIN
FB BAJADA
FF/FB ALLUVIAL FAN/VALLEY FILL

NOTE: REFER TO TABLE 1 FOR A DETAILED EXPLANATION OF LANDFORMS

FIGURE 4

are represented by very dark colors, browns and greens, with relatively sharp and steep outer slopes and flat upper surfaces.

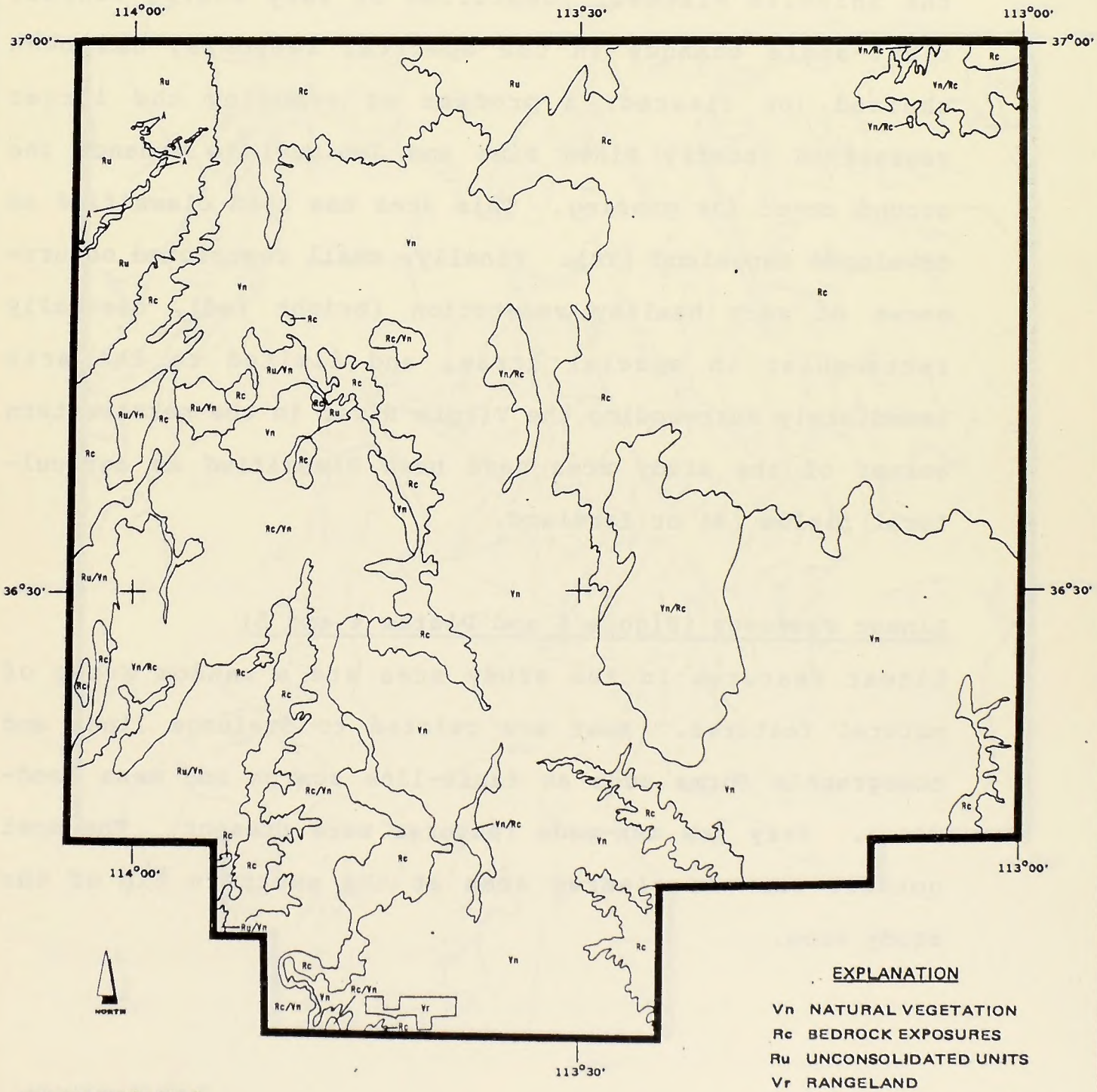
The most extensive area of rugged, exposed bedrock classified as mountain (M) is along the Virgin-Beaverdam Mountain trend. These areas are characterized by a high density of small drainages, and steep, irregular, terrain indicated by many shadowed areas suggestive of mountainous topography.

West of the mountain area and east of the Virgin River is a blue-green, fan-like area of extensive coalescing alluvial fans identified as bajada (FB). The spectral response is primarily a function of the desert pavement and desert varnish characteristics of the bajada surface. West and north of the Virgin River is a yellow-white area representative of a combination of small alluvial fans and valley fill deposits identified as FF/FV. This area is indicative of a wide, shallow sloped area of unconsolidated deposits.

Cover Types (Figure 5 and Plates 4 and 5)

The vegetation in the study area is primarily represented by varying intensities of reds and red-browns on the Landsat image. These areas have not been subdivided into individual categories but combined into areas identified as natural vegetation (Vn). In places where vegetation and rock outcrop, either consolidated (Rc) or unconsolidated (Ru) are

# COVER TYPES




EXPLANATION

Vn NATURAL VEGETATION
Rc BEDROCK EXPOSURES
Ru UNCONSOLIDATED UNITS
Vr RANGELAND
A AGRICULTURAL FIELDS

APPROXIMATE SCALE

0 5 10 MILES

0 10 20 KILOMETERS

NOTE: REFER TO TABLE 1 FOR DETAILED EXPLANATION OF COVER TYPES

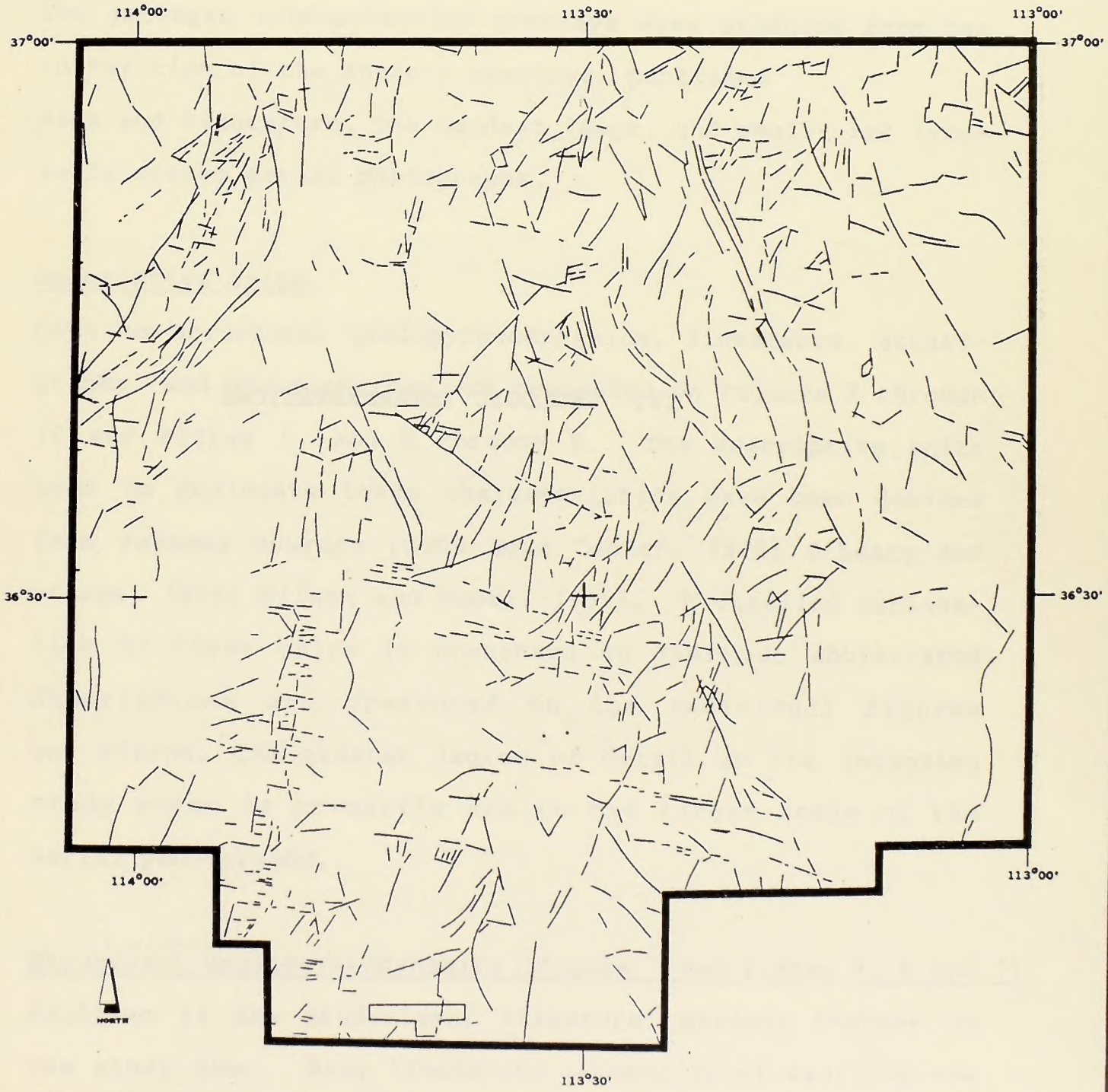
FIGURE 5

nearly equal, they are combined as Rc/Vn or Ru/Vn. Most of the vegetation areas can be further classified as undeveloped rangeland. One small area on the southern end of the Shivwits Plateau, identified by very sharp, linear, right-angle changes in the spectral response, has been chained, or cleared; a process of removing the larger vegetation (mostly Pinon Pine and Juniper) to enhance the ground cover for grazing. This area has been classified as developed rangeland (Vr). Finally, small restricted occurrences of very healthy vegetation (bright red), basically rectangular in spacial array, and limited to the area immediately surrounding the Virgin River in the northwestern corner of the study area have been classified as agricultural fields (A) or farmland.

Linear Features (Figure 6 and Plates 4 and 5)

Linear features in the study area are a random group of natural features. Most are related to drainage lines and topographic forms such as fault-line scarps and mesa landforms. Very few man-made features were present. The most notable was the cleared area at the southern tip of the study area.

# LINEAR FEATURES




APPROXIMATE SCALE

0 5 10 MILES

0 10 20 KILOMETERS

NOTE: REFER TO TABLE 1 FOR EXPLANATION OF LINEAR FEATURES

FIGURE 6

# IV. GEOLOGIC INTERPRETATIONS

# IV. GEOLOGIC INTERPRETATIONS

## Integration of Data

The geologic interpretation overlays were produced from the integration of the Phase I overlays, published maps and literature, the Landsat image, and small- and large-scale stereo aerial photographs.

### Descriptive Units

Data on structural geology/geodynamics, lineaments, stratigraphy, and geomorphology are presented on Figures 7 through 10 and Plates 1, and 6 through 9. The descriptive units used to delineate these characteristics have been devised from various sources (EROS Data Center, 1978; O'Leary and others, 1976; Wilson and Moore, 1959). A detailed explanation of these units is presented in Table 2; abbreviated descriptions are presented on the individual Figures and Plates. The greater degree of detail in the intensive study areas is primarily due to the larger scale of the aerial photographs.

### Structural Geology/Geodynamics (Figure 7 and Plates 1, 6 and 7)

Faulting is the predominant structural geology feature in the study area. Many lineaments suggestive of faulting can be interpreted in the study area from the Landsat image and aerial photographs. The main literature faults, the Grand

TABLE 2

DESCRIPTIVE UNITS FOR GEOLOGICAL INTERPRETATIONS (PHASE II)

| Symbol | Description |
|---|---|
| | **Geologic Structure/Geodynamics** |
| U<br>D | Fault identified in literature with corresponding lineament on Landstat image; dashed where location approximate (u=upthrown side, D=downthrown side). |
| U | Fault only identified in literature (u=upthrown side; D=downthrown side). |
| | ANTICLINE: arrow indicates direction of plunge. |
| | SYNCLINE: arrown indicates direction of plunge. |
| | **Lineaments** |
| | LINEAMENT: All lineaments are mapped according to the definition of lineament by O'Leary (1976): |
| | "Lineament. L. linea = line + L. mentum = akin to; hence, akin to or like a line. A lineament is a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumable reflects a subsurface phenomenon." |
| | **Stratigraphy** |
| Qa | Undifferentiated Quaternary sediments |
| Qc | Quaternary colluvium |
| Qt | Quaternary terrace deposits |
| Qls | Quaternary landslide |
| QTb | Quaternary/Tertiary volcanic rocks, primarily basalt |
| Ts | Undifferentiated Tertiary sediments |
| Kcw | Cretaceous Cottonwood Wash beds. |
| Jn | Jurassic Navajo Sandstone |
| Ꞧc | Triassic Chinle Formation |

TABLE 2 (Continued)

DESCRIPTIVE UNITS FOR GEOLOGICAL INTERPRETATIONS (PHASE II)

| Symbol | Description |
|---|---|
| Ꞧs | Triassic Shinarump Conglomerate Member of the Chinle Formation |
| Ꞧm | Triassic Moenkopi Formation |
| Pk | Permian Kaibab Limestone Formation |
| Pkc | Undifferentiated Permian Kaibab Limestone and Coconino Sandstone |
| Ps | Permian Supai Formation |
| Pu | Undifferentiated Paleozoic rocks |
| pЄu | Undifferentiated Precambrian rocks |

Geomorphology

| | |
|---|---|
| FF | ALLUVIAL FAN: areas characterized by gently sloping topography, a general fan-like form in plan view apexing where drainage lines emerge from mountainous terrain, and anastomosing drainage lines. |
| FB | BAJADA: areas characterized by sloping topography developed as a continuous apron flanking major mountain ranges (coalesced fans). |
| FT | TERRACE: areas characterized by very gentle slopes with a steeper ascending slope on one side and a steeper descending slope on the opposite side. Restricted to the area along the Virgin River in the study area. |
| FC | COLLUVIUM: natural areas composed of loose and unconsolidated deposits, usually at the foot of a slope or cliff and primarily deposited by gravity. |
| FV | FILLED VALLEY/VALLEY FILL: areas characterized by flat, irregular shape, braided drainage pattern, typically located in intramountain valleys. |
| VF | VOLCANIC FORM: landforms directly attributable to volcanic eruptions. Includes volcanic cones; landforms with conical or subcircular shape with steep slopes, and radial drainage, and volcanic flows; landforms with steep, cliff-like outer edges that form plateau - or mesa-like features typically associated with volcanic cones, and filling or covering pre-existing topography. |

TABLE 2 (Continued)

DESCRIPTIVE UNITS FOR GEOLOGICAL INTERPRETATIONS (PHASE II)

| Symbol | Description |
|---|---|
| P | PLATEAU: areas characterized by relatively flat topography developed over a regional extent. |
| PD | DISSECTED PLATEAU: highly dissected (eroded) areas of plateau. |
| E | ESCARPMENT: cliff-like areas characterized by steep topography with gentler slopes both above and below. |
| M | MOUNTAIN: terrain characterized by steep, irregular topography, numerous first order drainages, and sparce vegetation. |
| HB | HOGBACK (FLATIRON): a long, narrow ridge or series of hills, structurally controlled by the presence of homoclinal sedimentary strata that dip steeply. |

# STRUCTURAL GEOLOGY/GEODYNAMICS

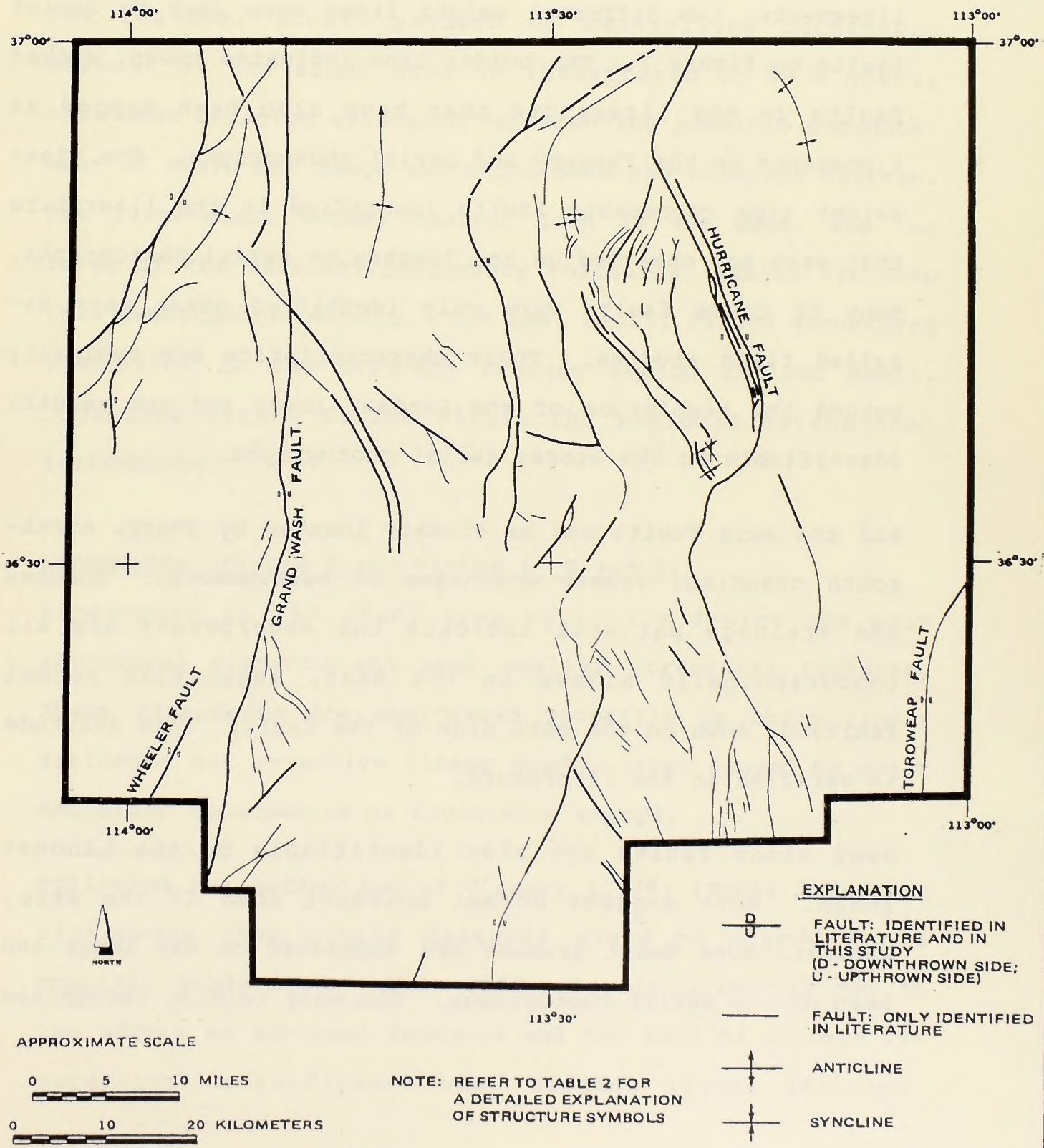



FIGURE 7

Wash, Wheeler, Hurricane, and Toroweap are all coincident with lineaments on the imagery and photographs. To accentuate this association between known faults and mapped lineaments, two different weight lines were used to depict faults on Figure 7. The bolder line indicates known, mapped faults in the literature that have also been mapped as lineaments on the imagery and aerial photographs. The finer weight line represents faults identified in the literature that were not observed on the imagery or aerial photographs. Many of these faults were only identified after very detailed field studies. Their characteristics are typically beyond the resolution of the Landsat image and not readily identifiable on the stereo aerial photographs.

All the main faults can be closely located by sharp, north-south trending, linear drainages or escarpments. Shadows and drainage patterns indicate the escarpments are all topographically higher on the east, suggesting normal faulting, down on the west side of the fault. This attitude is verified in the literature.

Many minor faults are also identifiable on the Landsat image. Most suggest normal movement down to the west. However, some small grabens are suggested on the image and seen on the aerial photographs. The only folding recognized

in the remote sensing analysis was in the Virgin Mountains. The other, small folds identified were all from literature sources.

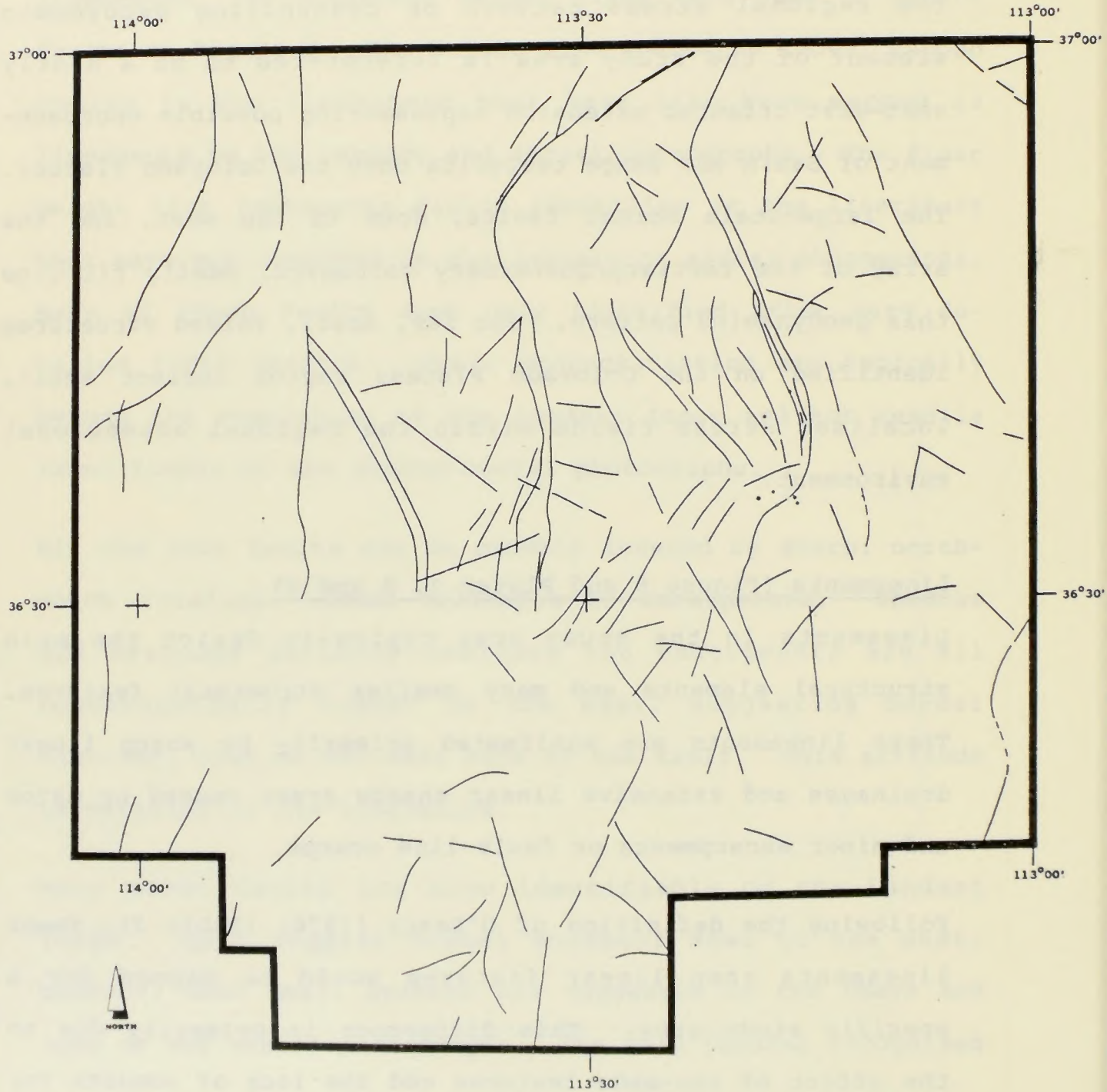
The regional stress pattern or controlling geodynamic element of the study area is interpreted to be a nearly east-west oriented extension representing possible encroachment of Basin and Range tectonics onto the Colorado Plateau. The large-scale normal faults, down to the west, and the array of the Tertiary/Quaternary volcanics, easily fit into this geodynamics pattern. The few, small, folded structures identified on the Colorado Plateau region reflect small, localized stress fields within the regional extensional environment.

Lineaments (Figure 8 and Plates 1, 8 and 9)

Lineaments in the study area typically depict the main structural elements and many smaller structural features. These lineaments are manifested primarily by sharp linear drainages and extensive linear shadow areas caused by major and minor escarpments or fault-line scarps.

Following the definition of O'Leary (1976) (Table 2), fewer lineaments than linear features would be mapped for a specific study area. This difference is primarily due to the effect of man-made features and the lack of concern for structural significance when mapping linear features.

# LINEAMENTS




APPROXIMATE SCALE

0 5 10 MILES

0 10 20 KILOMETERS

NOTE: REFER TO TABLE 2 FOR EXPLANATION OF LINEAMENTS

FIGURE 8

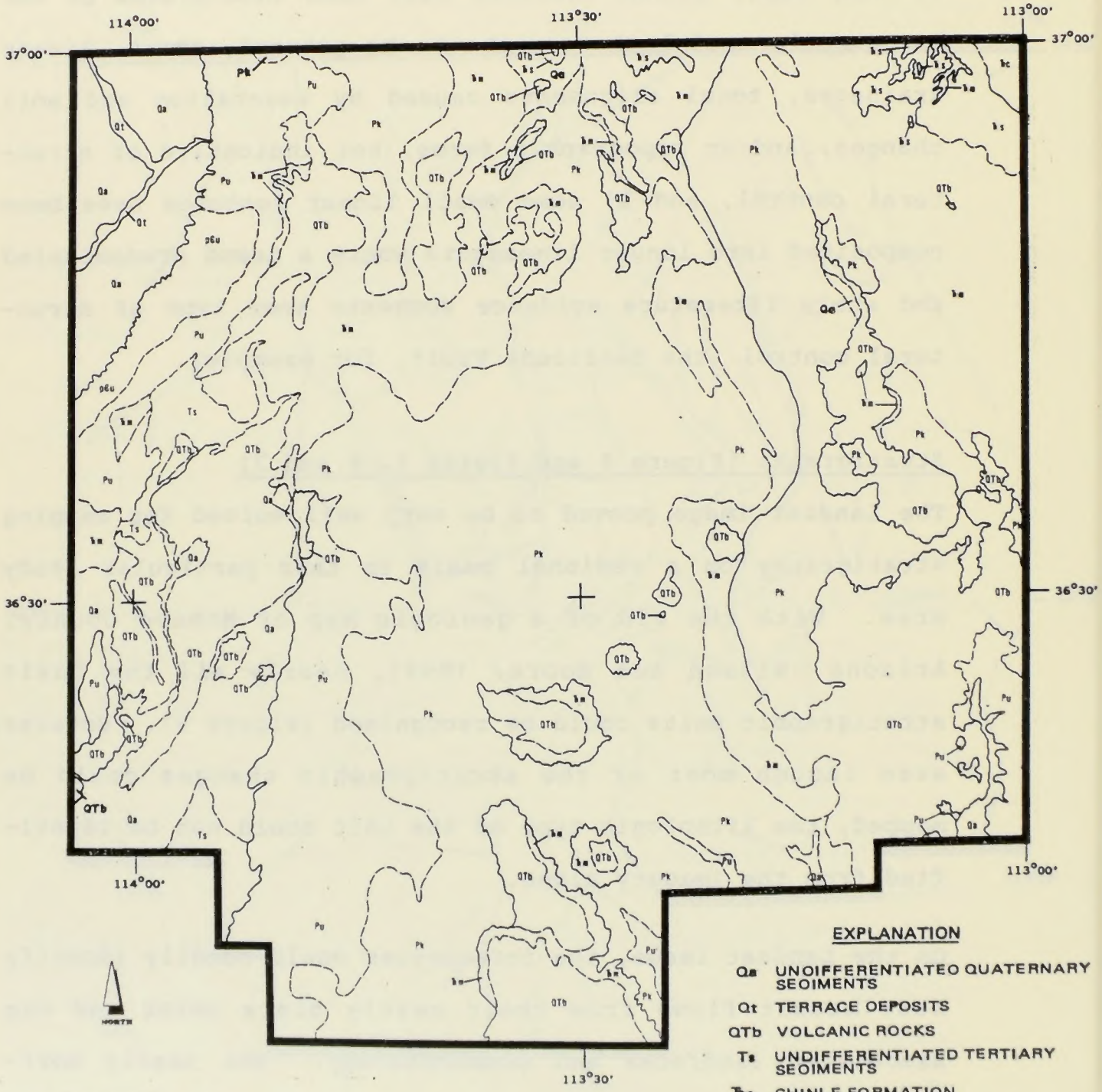
The regional study area is unusual in that very few man-made features were present. Still, fewer lineaments than linear features were annotated, primarily for the following reasons: 1) many small linear features have been interpreted on the large-scale aerial photographs to be natural, short, linear drainages, tonal alignments caused by vegetation and soil changes, and/or topographic forms, not indicative of structural control, and 2) some small linear features have been composited into longer lineaments where a trend predominated and where literature evidence suggests some type of structural control (the Hurricane Fault, for example).

Stratigraphy (Figure 9 and Plates 1, 6 and 7)

The Landsat image proved to be very well suited for mapping stratigraphy on a regional basis in this particular study area. With the aid of a geologic map of Mohave County, Arizona (Wilson and Moore, 1959), nearly all the basic stratigraphic units could be recognized (Figure 9). However, even though most of the stratigraphic changes could be mapped, the lithologic type of the unit could not be identified from the imagery alone.

On the Landsat image, the interpreter could readily identify most basalt flows from their nearly black color and the associated landforms and geomorphology. The nearly horizontal sedimentary sequence of the Grand Canyon Section

# STRATIGRAPHY




APPROXIMATE SCALE

0 5 10 MILES

0 10 20 KILOMETERS

NOTE: REFER TO TABLE 2 FOR EXPLANATION OF STRATIGRAPHIC UNITS

**EXPLANATION**

- Qa UNOIFFERENTIATEO QUATERNARY SEOIMENTS
- Qt TERRACE OEPOSITS
- QTb VOLCANIC ROCKS
- Ts UNDIFFERENTIATED TERTIARY SEOIMENTS
- Ꞧc CHINLE FORMATION
- Ꞧs SHINARUMP CONGLOMERATE
- Ꞧm MOENKOPI FORMATION
- Pk KAIBAB LIMESTONE FORMATION
- Pu UNOIFFERENTIATEO PALEOZOIC ROCKS
- pЄu UNOIFFERENTIATED PRECAMBRIAN ROCKS

FIGURE 9

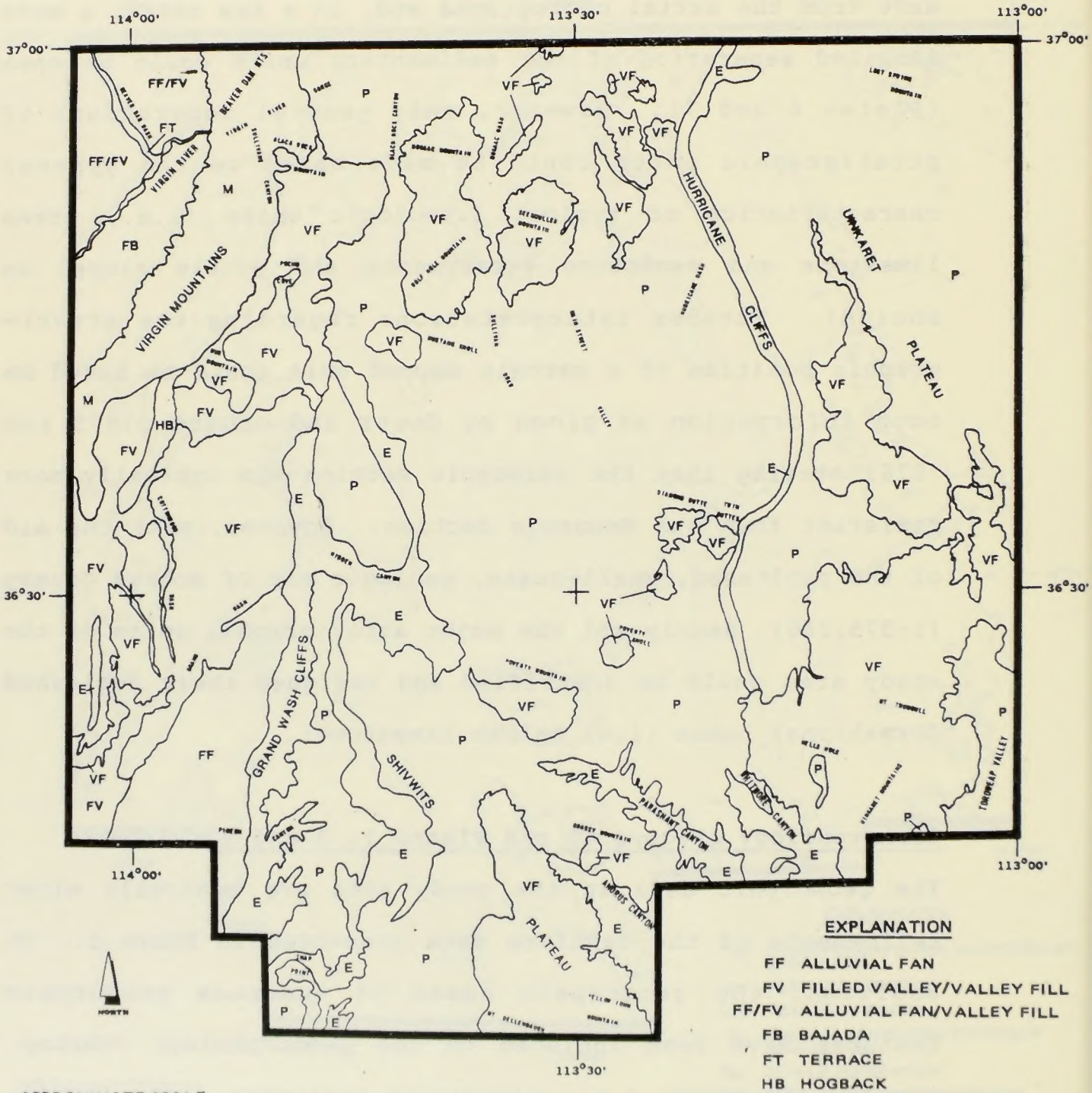
could be distinguished from the surrounding volcanics, alluvium, and deformed crystallines in the Virgin Mountains.

A better identification of the stratigraphic units could be made from the aerial photographs and, in a few cases, a more detailed separation of the sedimentary units could be seen (Plates 6 and 7). However, only general separations of stratigraphic units could be made based on the general characteristics of typical lithologic units (i.e., steep limestone and sandstone escarpments and gentle slopes on shales). Further interpretations regarding the stratigraphic position of a certain mapped unit could be based on such information as given by Goetz and others (1975 and 1976) stating that the Paleozoic section was typically more resistant than the Mesozoic section. However, with the aid of the published, small-scale, geologic map of Mohave County (1:375,000), nearly all the major stratigraphic units of the study area could be identified and assigned their published formational names (i.e. Kaibab Limestone).

Geomorphology (Figure 10 and Plates 1, 8 and 9)

The geomorphic data in the study area are basically minor refinements of the landform data presented in Phase I. In addition, the geographic names of numerous geomorphic features have been included on the geomorphology overlay. Minor refinements, i.e., separating colluvium from alluvium

# GEOMORPHOLOGY


114°00'
113°30'
113°00'
37°00'
36°30'
VIRGIN MOUNTAINS
VIRGIN RIVER
BEAVER DAM MTS
HURRICANE CLIFFS
UNKARET PLATEAU
GRAND WASH CLIFFS
SHIVWITS
PLATEAU
PARASHANT CANYON
ANDROS CANYON
TOROWEAP VALLEY
NORTH
FF/FV
FT
FF/FV
FB
M
VF
P
E
FV
HB
FF
M
VF
E
P
VF
E
P
VF
E
P

and dissected plateau from plateau, in the geomorphic interpretations can be seen in Plates 8 and 9 where interpretation of large-scale aerial photographs has allowed more detailed separations of classification units.

# V. DISCUSSION OF GEM RESOURCE POTENTIAL

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GEM resource potential for the study has been divided into four main categories: 1) leasable energy resources, 2) salable industrial resources, 3) locatable mineral resources, and 4) water resources. The following discussion presents the interpreted resource potential of the regional study area and specifically of the two intensive study areas $I_1$ and $I_2$.

## Leasable Energy Resources

### Oil and Gas

Several oil and gas shows have been reported in the Paleozoic/ Mesozoic stratigraphic section in the study area but there is no production from these formations in northwestern Arizona. Very few exploratory wells have been drilled in the regional study area. Nearly all of these tests were on the east side of the Hurricane Fault. Approximately 18 test wells have been drilled and all are presently classified dry and abandoned (Peirce and others, 1970). The average spacing of the test wells for northwestern Arizona is one well per 1040 $km^2$ (400 $mi^2$) (Giardina, 1979). However, renewed interest based on new finds related to the overthrust belt which extends from Mexico into Canada and passes through northwestern Arizona strongly suggests potential for oil and gas throughout the study area (Keith, 1979).

There is one test well in $I_1$ located in Section 35, Township 39 N., Range 13W. (Giardina, 1979). This well had numerous shows ranging from slight to heavy dead oil stains from 230 m (760 ft) to 1125 m (3710 ft) in depth. The potential for oil and gas in the Paleozoic/Mesozoic section, the insufficient exploration, and the proximity of the overthrust belt, suggests that all of $I_1$, except possibly the rugged Virgin Mountains, be classified as having potential for future production of oil and gas (Figure 11 and Plate 10).

There are no test wells located in intensive study area $I_2$. Peirce and others (1970) report that no wells have been drilled closer than 40 km (25 mi.) from the Colorado River. This relates to the possible release or decrease in pressure of hydrocarbons from exposing the Paleozoic stratigraphic section by the deep incision of the Colorado River. However, with the renewed interest in the overthrust belt and the production from extreme depths, well beyond the incision of the Colorado River, the entire study area $I_2$ becomes an area of potential oil and gas discovery (Figure 12 and Plate 11).

Coal

There are no known or interpreted coal deposits in the study area.

# INTENSIVE STUDY AREA I
# GEM RESOURCE POTENTIAL

EXPLANATION

- OIL AND GAS
- SAND AND GRAVEL
- GENERAL PURPOSE RIP RAP
- MINERAL
- × CLAIM LOCATION
- SPRING

NORTH

0 2 4 MILES

0 3 6 KILOMETERS

FIGURE 11

# INTENSIVE STUDY AREA $I_2$
# GEM RESOURCE POTENTIAL

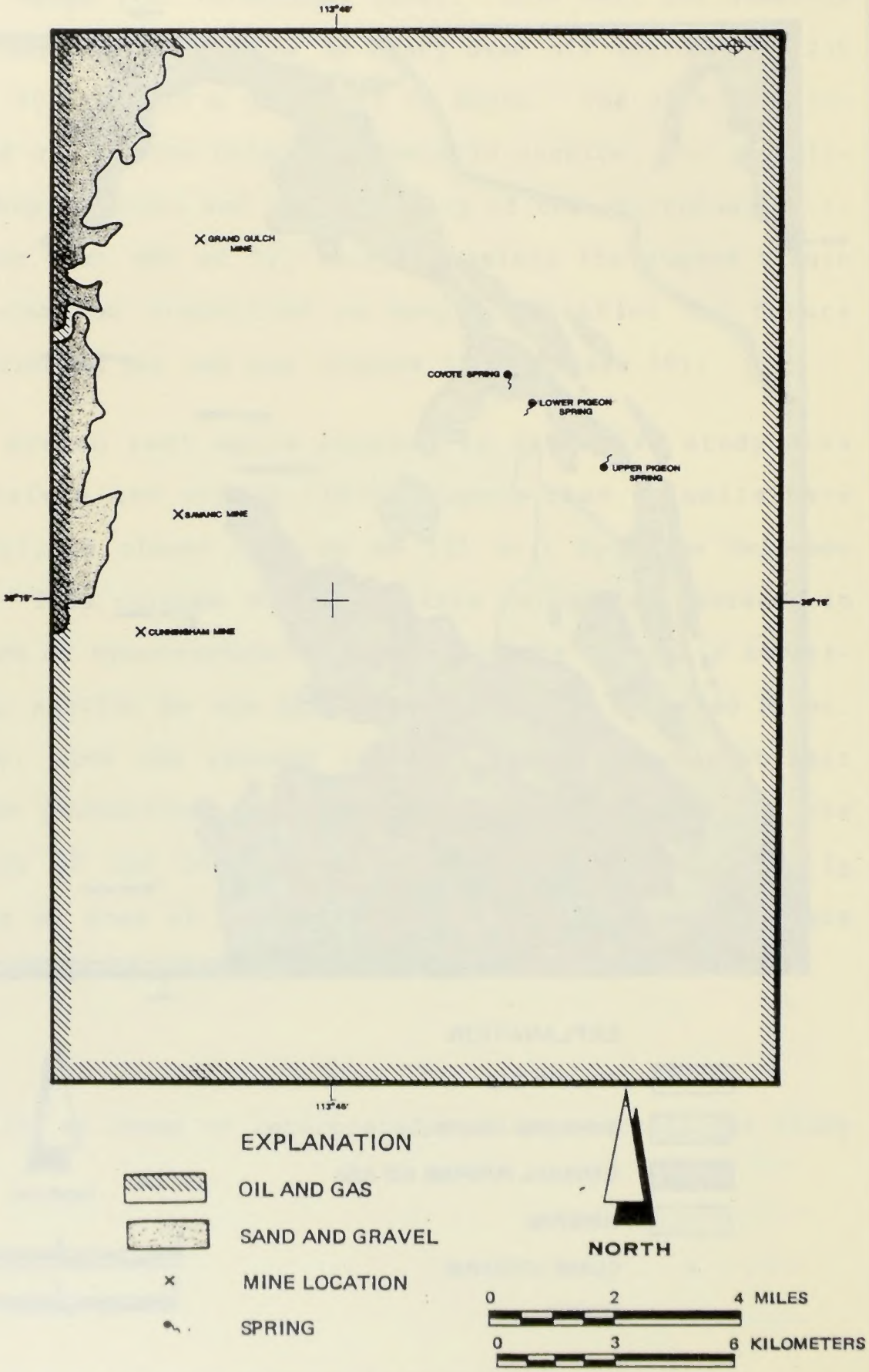


FIGURE 12

Geothermal

There is one recorded hot spring, Pakoon Springs, in the regional study area located west of $I_2$ in Grand Wash. This is not a geothermal resource area but simply a hot spring. Therefore no potential for geothermal resources is present in either $I_1$, or $I_2$.

## Salable Industrial Resources

Sand and Gravel

Low grade sand and gravel resources and general purpose aggregate resources are present throughout the regional study area. The sand and gravel are present as alluvial fan, bajada, valley fill, terrace, and active channel deposits. In $I_1$ potential sand and gravel resources are present on the west side of the Virgin Mountains as alluvial fan/bajada deposits and east and southeast of the Virgin Mountains as valley fill and active alluvium or channel fill deposits (Figure 11 and Plate 10). Potential for sand and gravel resources is very limited in $I_2$ and is primarily restricted to the Quaternary and Tertiary sediments west of the Grand Wash Cliffs (Figure 12 and Plate 11).

General Purpose Aggregate

Quaternary/Tertiary volcanic flows (basalt and andesite) are sources of rip rap or general purpose crusher feed in the

study area (Arizona Highway Department, 1973). Extensive volcanic flow deposits are present in $I_1$ giving that area a potential for general purpose aggregate (Figure 11 and Plate 10). No Quaternary/ Tertiary volcanic flows exist in $I_2$ and therefore no potential for general purpose aggregate is present (Figure 12 and Plate 11).

## Locatable Mineral Resources

Northwestern Arizona has documented deposits of many minerals. Claims, prospects, and/or mines are recorded for the following mineral products: uranium, vanadium, rare earths, nickel, tungsten, thorium, beryllium, lithium, zirconium, manganese, gypsum, halite, mica, copper, kyanite, andalucite, and sillmanite. Beryllium in the form of Beryl and Chrysoberyl is found in pegmatite dikes in Precambrian crystalline rocks in the Virgin Mountains. Cobalt and nickel are found in association with pyrrhotite and chalcopyrite in mafic dikes in the Virgin Mountains. Rare earths, xenotime and monazite, and thorium are found locally in the Precambrian granite gneisses and tungsten is found locally associated with the Precambrian crystalline rocks in the Virgin Mountains. Nearly all of these mineral occurrences are in the Virgin Mountains west and south of intensive study area $I_1$.

Immediately north and west of intensive study area $I_1$, are numerous gypsum deposits. The occurrences are from lenses

in the Permian redbeds, between the Kaibab and Toroweap formations. Some gypsum deposits have been open-pit mined and sold locally for agricultural use. These areas have been inactive since 1966 (USGS and others, 1969).

One claim is located in $I_1$ in the northern portion of Cottonwood Wash, east of the Virgin Mountains. The claim has registered local occurrences of very low grade uranium and vanadium. This mineralization is most likely associated with the Shinarump Member of the Chinle Formation. The USGS and others (1969) see no future potential for these small, low grade, local occurrences.

Therefore, because of all the reported mineral occurrences in the Virgin Mountains immediately outside $I_1$ and because of the unusual colors and suggested alterations in the mountains noted on aerial photographs and in the field, the entire Virgin Mountain area has been classified as an area of potential mineral resources (Figure 11 and Plate 10). In addition, the location of the one claim has also been included on the resource potential map for $I_1$.

Three inactive mines were identified in intensive study area $I_2$, the Grand Gulch, the Savanic, and the Cunningham mines. All three mines have had past productions of copper, silver, vanadium, iron, lead, and zinc, in excess of 100 tons. All produced primarily in the early 1900's from

underground but had some open-pit development. The mineralization occurred along the fractured periphery of plug-like bodies in unstratified sandstones and limestones. All the mines are very localized, structurally controlled occurrences with no potential of expanding throughout $I_2$. Therefore, no mineral resource potential has been identified in $I_2$ and only the location of the three mines has been shown on Figure 12 and Plate 11.

## Water Resources

### Surface Water

All surface water in the study area flows through ephemeral or intermittant drainages to the Colorado River. Runoff is primarily attributed to precipitation especially in the more mountainous areas. The main potential for surface water in the regional study area is along the Virgin River where water is diverted for agricultural use. There is no surface water potential in either intensive study area except for a few small springs discussed under ground water. The only surface water is found in small, manmade, stock reservoirs which are dry part of each year.

### Ground Water

Ground-water movement is controlled by the large normal faults and the gentle northeastward slopes in the regional study area. The major ground-water area in the study area

is called the Virgin Trough (USGS and others, 1969) and is essentially synonymous in location with the Shivwits Plateau. Ground water in this area moves both to the Colorado and Virgin Rivers. Most of the water is contained in multiple-aquifer systems. Water yielding sedimentary rocks are primarily massive, fine-grained sandstones separated by impermeable siltstones and mudstones. The fine-grained character restricts rapid water movement and produces small well yields. There are no areas of concentrated pumping but a few wells are producing water for livestock use. Numerous small springs are identified in both intensive study areas (Figures 11 and 12, and Plates 10 and 11). The low yield of wells and springs suggests that the potential ground-water resources are negligible.

# VI. COMPARISON OF REMOTE SENSING DATA

## VI. COMPARISON OF REMOTE SENSING DATA

For a regional study presented at a scale of 1:250,000, the computer enhanced Landsat image, when supplemented with literature data, produced a very representative view of the geologic characteristics of the northwest Arizona test area. The Landsat data was also representative in the intensive study areas although greater detail was obtainable from the aerial photographs. A comparison of these remote sensing data is presented in Table 3.

Examination of aerial photographs will usually improve accuracy and detail of interpretations over the Landsat image. This is inherent in the fundamental differences in resolution and stereo viewing capability. As one increases the scale of the aerial photograph, 1:120,000 to 1:30,000, the degree of detail (resolution) and accuracy also increases. This ability to improve detail, when necessary, is important in mapping stratigraphic units, 1st order stream channels, small landforms and structural features, and for helping separate lineaments from linear features and determining the attitude of faults and structures.

The Landsat image, as applied to the identification of GEM resource potential, was best suited for defining the regional structural/tectonic elements through identification of lineaments and faults, and the gross stratigraphic and

## TABLE 3
## COMPARISON OF REMOTE SENSING DATA ON THE NORTHWEST ARIZONA TEST AREA

| Remote Sensing Data | Computer Enhanced Landsat | Computer Enhanced Landsat Plus Literature | Aerial Photographs | Aerial Photographs Plus Literature | Comments |
|---|---|---|---|---|---|
| Geologic Characteristics | | | | | |
| Drainage Patterns | Identify major and minor streams and tributaries. 1st order streams questionable and tedious. Accuracy marginal. | Same as Landsat. May get minimal help from large-scale topographic maps. | Easy to map all stream channels and tributaries including 1st order. More accurate. | Same as aerial photographs. | Detail and accuracy greater with air photos. Much faster with Landsat. |
| Landforms | Identify nearly all major land forms, especially when familiar with area. | Same as Landsat. Can improve accuracy at times. | Identify all major landforms. Minor improvement over Landsat. Can be more detailed if necessary. | Same as aerial photographs. | Probably better to use Landsat because of time to produce minor improvements. |
| Cover Types | Very general classification, primarily based on color and texture. Can do detailed computer classification but beyond scope of work. | Minor improvements unless specific data, i.e. vegetation and land use, are available. Will improve classes if this data is available. | Identify more vegetation changes and more detailed classification if necessary. | Same as Landsat plus literature. | Air photos better for all but most general classification. Landsat best if more detail is not necessary. |
| Linear Features | Identify large number. Excellent for regional study. | No help in mapping except to suggest origin of linear features. | May identify some smaller than Landsat resolution. Regional overview not as easy. Can identify possible origin of linear features. | Same as Landsat plus literature. | Landsat probably best when origin of feature is not important. A combination of Landsat and air photos is preferable. |
| Structure/ Geodynamics | Identify major and minor structures and faults. Excellent for regional trends and overview. Minimal help in determining attitudes and specific characteristics of structures. | Complete understanding of faults and structures by identifying attitudes. Will identify more structures than found on Landsat alone. | Identify most if not all faults and structures. Can help identify attitudes. Some restriction with regional trends. | Best identification of faults, structures and their attitudes. | Landsat good for regional start. Best results from using all three data sources. |
| Lineaments | Same as linear features | Helps distinguish linear features from lineaments. | Better definition of lineaments and helps separate from linear features. | Best separation of lineaments from linear features. More precise. Can categorize lineaments. | Landsat good starting point but must use air photos and literature to separate lineaments from linear features. |
| Stratigraphy | Identify certain lithologic changes but can not classify the types. | Identified a large percentage of the lithologic units in the regional study area. | Identify more lithologic units and with better accuracy. Can make interpretations as to rock type. | Produce accurate geologic map of study area. Only limited by the scale of the air photos and literature. | Detail quite good with Landsat in this case. Usually much better with air photos. A combination of the two is preferable and most economical. |
| Geomorphology | Identify most geomorphic units and geograhic locations. | More accurate and complete unit identification and geographic locations. | Identify all geomorphic units more accurately. Minor improvement over Landsat. | Same as aerial photographs plus literature. | Best and most economical product from a combination of the two. |

geomorphic characteristics. Some of these characteristics are directly related to identifying specific resources, i.e. alluvial fan/bajada units directly relate to potential sand and gravel resources. More often though, these characteristics are a part of a geologic model developed by the investigator to predict resource potential, i.e. faults combined with knowledge of the subsurface structure and stratigraphy, and an understanding of hydrocarbon accumulation to predict oil and gas potential.

The aerial photographs were best suited for further detail of the gross features identified on the Landsat image. This includes greater detail of the structural features and stratigraphic units. Localized structural and lithologic features such as dikes, pegmatites, and alteration zones (tonal anomalies) can be seen on aerial photographs and are directly applicable to identifying resource potential, i.e. small areas of the Shinarump Member of the Chinle Formation have been associated with uranium deposits. As with the Landsat data, the aerial photograph data are most frequently used by the interpreter in a working geologic model to predict resource potential, i.e. the location of channel and terrace alluvial deposits combined with chemical and mechanical analyses to predict significant mineral occurrences.

In general, the computer enhanced Landsat image was an excellent starting point for a GEM resource potential evaluation. Aerial photographs improved accuracy and added important detail. These characteristics were then included in numerous models for predicting resource potential.

# VII. SUITABILITY OF THE EMPLOYED METHODOLOGY AND RECOMMENDATIONS

# VII. SUITABILITY OF THE EMPLOYED METHODOLOGY AND RECOMMENDATIONS

## Discussion of Applied Method

The methodology used in this study has proved to be satisfactory only for parts of a total GEM resource potential evaluation. The specific applicability of the individual geologic interpretation overlays is presented on Table 4. This table shows that the specific data collected and generated were all applicable, though in varying degrees to the evaluation of the GEM resource. The remote sensing data, when combined with literature, formed a sufficient data base to evaluate salable industrial resources, leasable energy resources, and water resources, but were basically incomplete for proper evaluation of the locatable mineral resources of the study area.

The remote sensing data provided valuable information towards the understanding of the study area GEM resources, but without the additional data obtained through the literature, and the knowledge of the trained evaluator, land management decisions based on these data alone would not be satisfactory. The following discussion addresses the applied methodology and recommendations on how to provide the additional required data to make the study sufficient to evaluate the total GEM resource potential.

## TABLE 4
## APPLICABILITY OF THE GEOLOGIC INTERPRETATION DATA TO THE GEM RESOURCE POTENTIAL

| DATA SOURCES | | INFERRED GEOLOGY, ENERGY, AND MINERAL RESOURCES | | | |
|---|---|---|---|---|---|
| | | LOCATABLE | SALABLE INDUSTRIAL | LEASABLE ENERGY | WATER |
| | | GOLD, URANIUM, ETC. | SAND AND GRAVEL, LIMESTONE | COAL, OIL AND GAS, ETC. | SURFACE AND GROUND |
| LITERATURE DATA | | 2 | 2 | 2 | 2 |
| GEOLOGIC INTERPRETATION OVERLAYS | STRUCTURAL GEOLOGY/ GEODYNAMICS | 2 | 1 | 2 | 2 |
| | STRATIGRAPHY/ LITHOLOGY | 2 | 2 | 2 | 2 |
| | GEOMORPHOLOGY | 1 | 2 | 1 | 1 |
| | LINEAMENTS | 2 | 1 | 2 | 1 |
| FIELD RECONNAISSANCE* | | 2 | 2 | 2 | 2 |

*FIELD RECONNAISSANCE AS LIMITED FOR THIS CONTRACT IS CONSIDERED INADEQUATE FOR SUFFICIENT EVALUATION OF LOCATABLE MINERAL RESOURCES.

EXPLANATION

1. IMPORTANT
2. VERY IMPORTANT

Table 5 presents the overall applicability of the data sources and combinations thereof used in this study to the understanding of the GEM resource potential of the northwestern Arizona study area. The table shows that alone, Landsat data, as used in this study, is not sufficient to develop the necessary data base for any resource category evaluated. Interpretations of larger-scale aerial photographs add more detail and accuracy but still alone or in combination with Landsat, do not develop a data base on which to make defendable land management decisions. The only exception is surface-water resources, where large-scale color infrared aerial photographs are probably sufficient to define the surface-water resources, but not the ground-water resources.

The most reliable source of information for the data base of the Arizona test area was the published literature (Table 5). Marginal to satisfactory data on which to base management decisions were found in the literature. However, these data were lacking substantial background information, available from the remote sensing tools. When literature data was combined with the individual remote sensing data the overall data base was improved. This improvement is primarily due to the need for understanding the subsurface conditions of the study area. Subsurface data from the literature, when combined with the data from the remote sensing sources allows the interpreter to fully develop

TABLE 5

APPLICABILITY OF THE DATA SOURCES TO THE GEM RESOURCE POTENTIAL

| DATA SOURCE | NATURAL RESOURCES | | | |
|---|---|---|---|---|
| | LOCATABLE MINERALS (URANIUM, GOLD, ETC.) | SALABLE INDUSTRIAL (SAND, GRAVEL, ETC.) | LEASABLE ENERGY (OIL, GAS, GEOTHERMAL) | WATER (SURFACE AND GROUND) |
| LANDSAT | *U* | *M* | *M* | *M* |
| AERIAL PHOTOGRAPHS | *U* | *M* | *M* | *S* |
| LITERATURE | *M* | *M* | *S - H* | *M - S* |
| LANDSAT & AIR PHOTOS | *U* | *M* | *M* | *S* |
| LANDSAT & LITERATURE | *M - S* | *S* | *S - H* | *S* |
| AIR PHOTOS & LITERATURE | *M - S* | *S - H* | *S - H* | *S - H* |
| ALL THREE | *M - S* | *H* | *H* | *H* |

*H:* HIGHLY SATISFACTORY – DATA BASE SUFFICIENT FOR MAKING EASILY DEFENDABLE LAND MANAGEMENT DECISIONS.

*S:* SATISFACTORY – DATA BASE WILL PRESENT GOOD PICTURE OF AREA BUT WILL PROBABLY LACK IMPORTANT BACKGROUND INFORMATION. LAND MANAGEMENT DECISIONS CAN PROBABLY BE MADE FROM THESE DATA BUT WILL BE HARDER TO DEFEND.

*M:* MARGINALLY SATISFACTORY – BARE MINIMUM DATA BASE TO DRAW DECISIONS FROM. WILL REQUIRE MANY ASSUMPTIONS. LAND MANAGEMENT DECISIONS WILL BE HARD TO DEFEND.

*U:* UNSATISFACTORY – DATA BASE INSUFFICIENT FOR MAKING LAND MANAGEMENT DECISIONS.

his working models of the specific resources. An understanding of the subsurface structure and stratigraphy is paramount in predicting the possible occurrence of oil and gas reserves, ground-water potential, and many forms of mineral occurrence.

The most complete data base was from a composite of information obtained from the three main data sources, Landsat, aerial photographs, and literature (Table 5). This data base is considered sufficient to evaluate the potential for salable industrial resources, leasable energy resources, and water resources. However, even the combination of the three data sources was not considered satisfactory to evaluate the locatable mineral resources of the study area.

## Recommendations

The recommended changes to the tested methodology are primarily aimed at expanding the field effort to provide an adequate data base to evaluate locatable mineral rsources. A detailed field mapping and sampling program, not just a few days field reconnaissance as was the case in this program, should provide the additional data needed to adequately evaluate the locatable mineral resources as well as strengthen the data base for the additional GEM resources.

However, it is also important to look at the overall available data base before initially setting-up a GEM resource

potential program. In general, the overall program categories, remote sensing, literature, and field mapping, are and will be the essential aspects of any GEM resource potential evaluation. But, the final program should not be decided until the available data for the particular study area is completely understood. For example, in the Arizona test area, a large volumn of literature was available. These literature data reflect many hours spent in the field in the study area and aid substantially in developing the geologic data base. In another study area literature may not be as available and more emphasis will have to be placed on field checking many of the structural geologic features interpreted from the Landsat image and aerial photographs, in addition to the detailed mapping and sampling for the locatable mineral resources.

In summary, the application of the employed methodology, remote sensing, literature, and minimum field reconnaissance, has provided certain data pertaining to the GEM resource potential of the Arizona test area. These data have proved to be sufficient to evaluate the salable industrial, leasable energy, and water resources, and insufficient to evaluate the locatable mineral resources. The major recommended modification is a detailed field and sampling program, not just a few days field reconnaissance. A detailed field study will provide sufficient data to evaluate the locatable mineral resources, and add to and strengthen the

data base on the remaining GEM resources. Additionally it is recommended that initial emphasis be placed on evaluating the available data prior to establishing the detailed methodology for a specific GEM resource potential evaluation.

# VIII. CONCLUSIONS

# VIII. CONCLUSIONS

The following conclusions are the result of the northwestern Arizona test study on the use of remote sensing data to evaluate GEM resource potential.

1. The tested methodology which utilized remote sensing, literature, and field checking should be adequate to perform a GEM resource potential evaluation when proper emphasis is placed on the separate tasks; emphasis is dependent on the data available for the specific study area.

2. The methodology proved adequate to evaluate salable industrial, leasable energy, and water resources but inadequate to evaluate the locatable mineral resource of the Arizona test area.

3. Alone or in combination with literature, the remote sensing data did not provide a sufficient data base to evaluate the total GEM resource potential. Independently, remote sensing data are only a tool used to help develop the necessary data base for the analysis.

# IX. REFERENCES

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